# Kaluza-Klein Dark Matter: a review

*Géraldine SERVANT*
Service de Physique Théorique- CEA/Saclay

*Based on work with*

-Tim Tait: hep-ph/0206071 (NPB)
hep-ph/0209262 (New J.Phys.)

-Bertone & Sigl: hep-ph/0211342 (PRD)

-Kaustubh Agashe: hep-ph/0403143 (PRL)
hep-ph/0411254 (JCAP)

-Dan Hooper: hep-ph/0502247

**ADD** models

$R \sim \mathrm{meV}^{-1}$ (flat)

only gravity
in bulk

- radion dark matter, m~meV
- branon dark matter
- KK graviton dark matter

(all fine-tuned)

**$\mathrm{TeV}^{-1}$** X-dims

$R \sim \mathrm{TeV}^{-1}$ (flat)

gauge bosons
in bulk

all SM fields
in bulk
"Universal" X-dims

- radion dark matter
m~meV; (fine-tuned)

- KK dark matter
WIMP!

Hierarchy pb solved

**Warped** geometries
(Randall-Sundrum)

(AdS)

$R \sim M_{Pl}^{-1}$ but $M_{KK} \sim \mathrm{TeV}$

- radion unstable

if GUT in bulk → - KK dark matter
WIMP!

# *WIMP KK dark matter*

So far, two working models :

## ✔ Universal Extra Dimensions (UED)

WIMP = Lightest KK particle (LKP)
stability symmetry = KK parity

## ✔ Warped GUTs

WIMP = Lightest $Z_3$ charged particle (LZP)
stability symmetry = $Z_3$ symmetry

+ a potential link between the LZP and baryogenesis...

# Literature on KK dark matter: the complete list

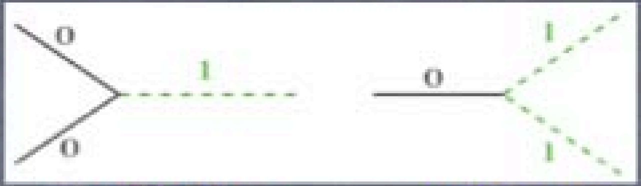
| | | |
|---|---|---|
| Kolb & Slansky '84 | Thought about it, but in 1984 $R^{-1}$~TeV was inconceivable... | |
| Dienes, Dudas & Gherghetta '99 | mentionned the idea in passing | |
| Mohapatra& Perez-Lorenzana '02 | | |
| Servant & Tait '02 | Detailed relic density calculation | KK dark matter in UED |
| Cheng, Feng & Matchev '02 | Direct and indirect detection | |
| Servant & Tait '02 | Direct detection | |
| Majumdar '02 | Direct detection | |
| Hooper & Kribs '02 | Prospects for neutrino telescopes | |
| Bertone, Servant & Sigl '02 | Indirect detection | |
| Hooper & Kribs '04 | Positron excess | |
| Bergstrom, Bringmann, Eriksson & Gustafsson '04 | Indirect detection | |
| Baltz & Hooper '04 | | |
| Bergstrom, Bringmann, Eriksson & Gustafsson II '04 | | |
| Kakizaki, Matsumoto, Sato & Senami '05 | A 2nd look at the relic density calculation | |
| + superWimp KK graviton papers | | |
| Agashe & Servant '04 | Model building, relic density, direct detection, collider signatures ... | Warped KK dark matter |
| Agashe & Servant II '04 | | |
| Hooper & Servant '05 | Indirect detection | |

# LKP dark matter in Universal Extra Dimensions

UED : ALL SM particles propagate into flat dimensions Appelquist, Cheng & Dobrescu '01

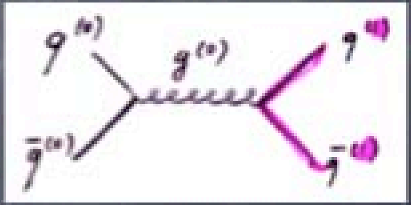
Translational invariance along the 5th dimension ⇒ Conservation of Kaluza-Klein number in the interactions of the effective 4D theory

For instance:



forbidden allowed

Consequence: n=1 KK excitations can only be produced by pairs



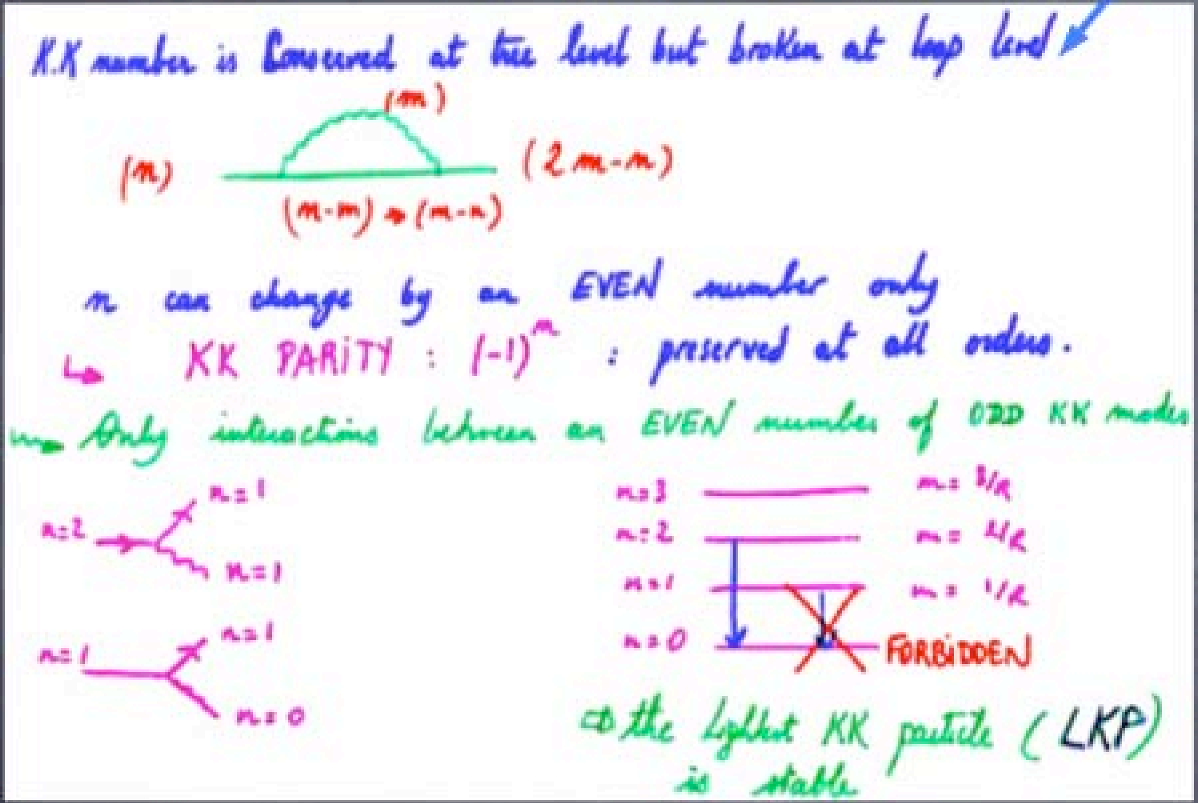
⇒ Collider constraints on 1/R are weak

$R^{-1} \gtrsim 300$ GeV for $\delta = 1$

$R^{-1} \gtrsim 500$ GeV for $\delta = 2$

Symmetry is broken by the orbifold but there remains a discrete symmetry called **Kaluza-Klein Parity: $(-1)^n$**

*by the orbifold we impose to recover a chiral theory*



K.K number is conserved at tree level but broken at loop level

n can change by an EVEN number only

↳ KK PARITY : $(-1)^n$ : preserved at all orders.

⇝ Only interactions between an EVEN number of ODD KK modes

⇒ the lightest KK particle (LKP) is stable

⇒Odd KK modes can only couple by pairs

⇒The Lightest KK mode (LKP) is stable

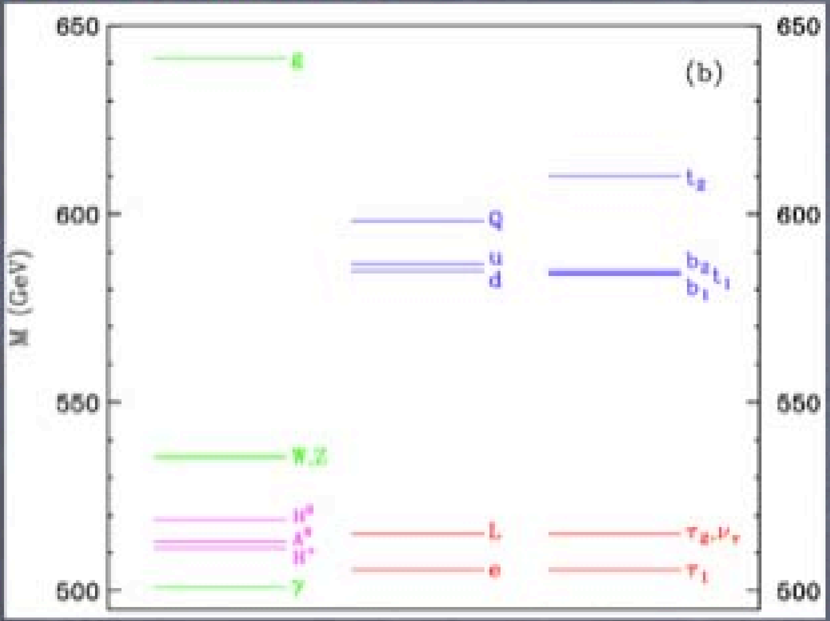
The Kaluza-Klein photon is an excellent dark matter candidate

Phenomenology is very similar to supersymmetry with conserved R-parity

All KK particles decay into the LKP

# 1-loop spectrum of 1rst KK modes

Cheng, Matchev & Schmaltz'02

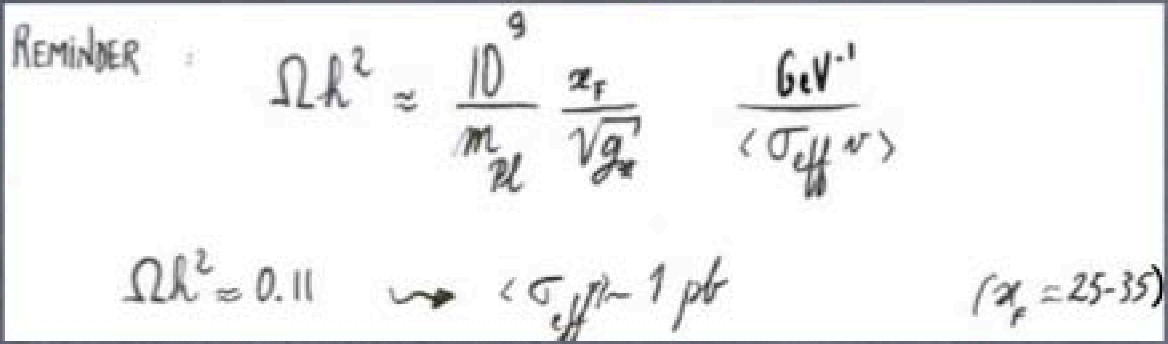


assuming:1/R=500 GeV, $\Lambda R = 20, m_h = 120$ GeV
and vanishing boundary terms at the cutoff $\Lambda$

⇒ LKP: most likely a $\gamma^1$ (actually a $B^1$)

Another intriguing possibility: LKP=KK graviton (see Feng & al.)

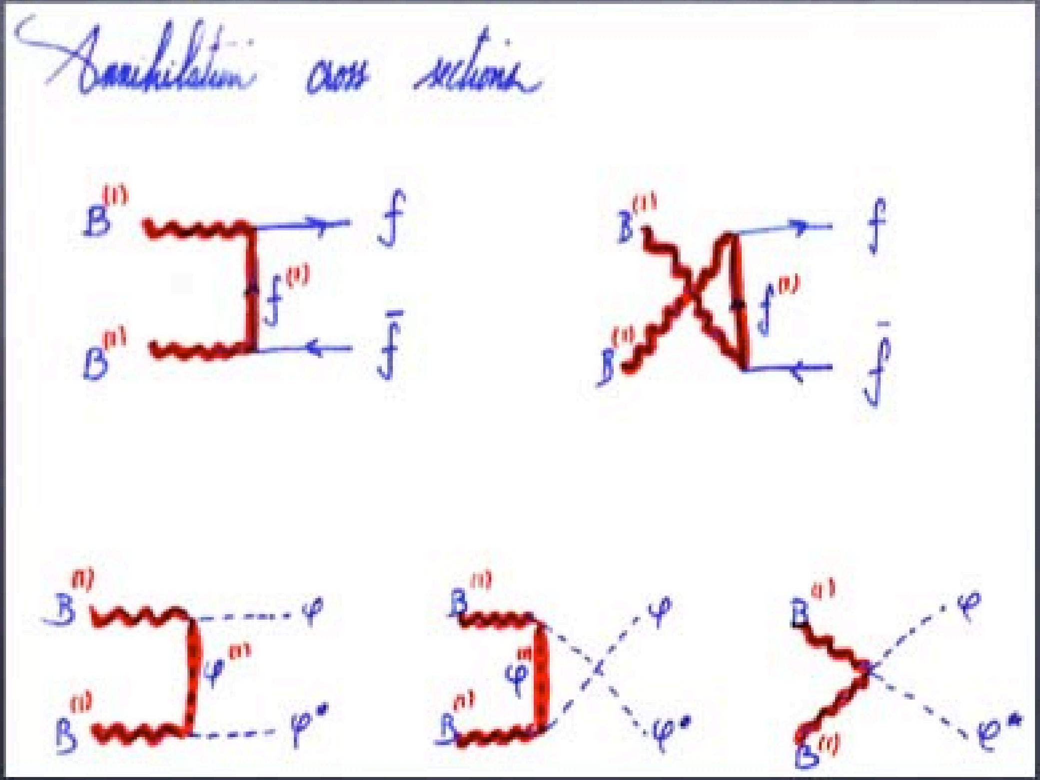
# Relic density predictions



REMINDER :

$$\Omega h^2 \approx \frac{10^9}{m_\chi} \frac{x_F}{\sqrt{g_*}} \frac{\text{GeV}^{-1}}{\langle \sigma_{\text{eff}} v \rangle}$$

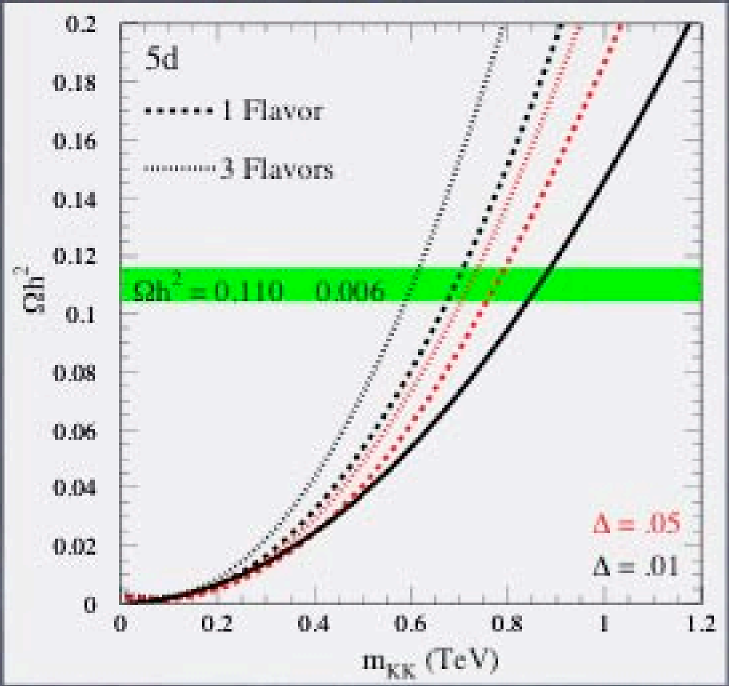
$\Omega h^2 \simeq 0.11 \rightsquigarrow \langle \sigma_{\text{eff}} v \rangle \sim 1$ pb  ($x_F = 25$-$35$)



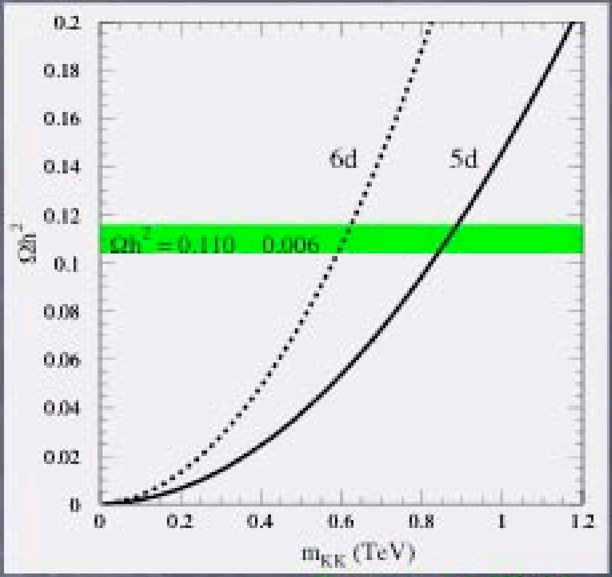
Annihilation cross sections

## ✔ Coannihilation effects

Servant-Tait



## ✔ Possible effect of additional dimension

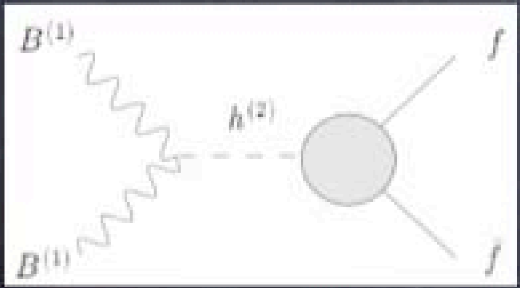


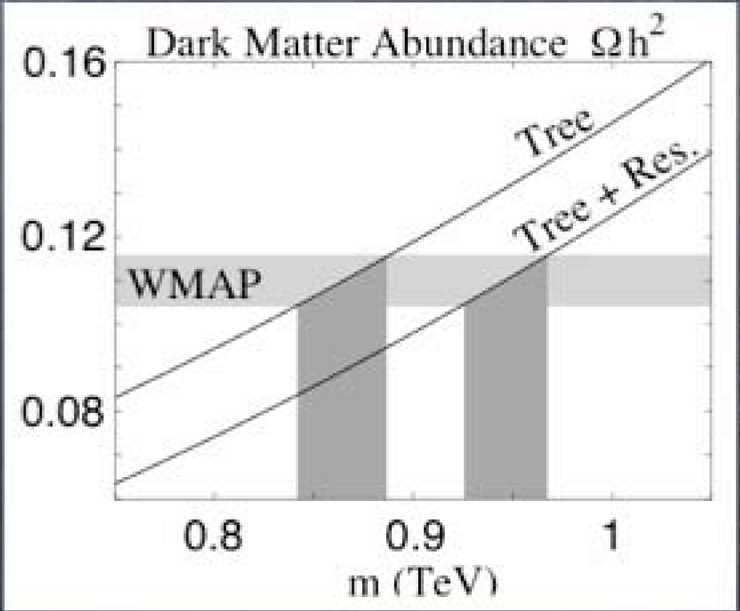
Servant-Tait

## ✔ Effect of 2nd KK modes

"natural KK resonance"

Kakizaki & al , hep-ph/0502059



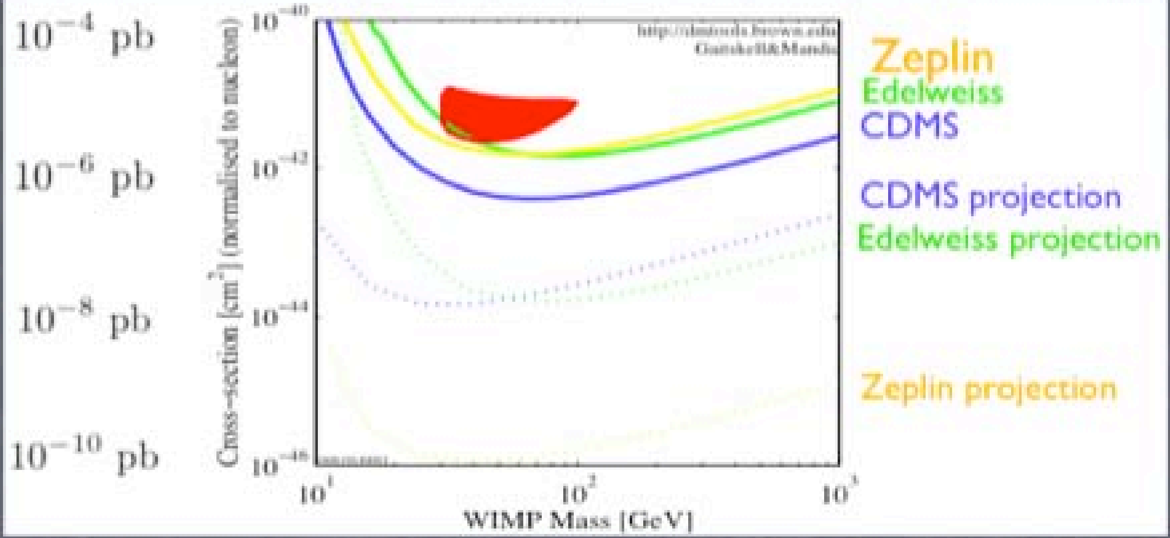


$\delta \equiv (m_{h^{(2)}} - 2m)/2m$

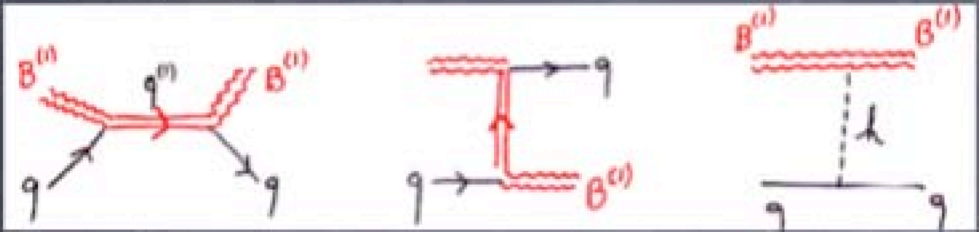
$\delta \sim 0.01$

# Direct detection

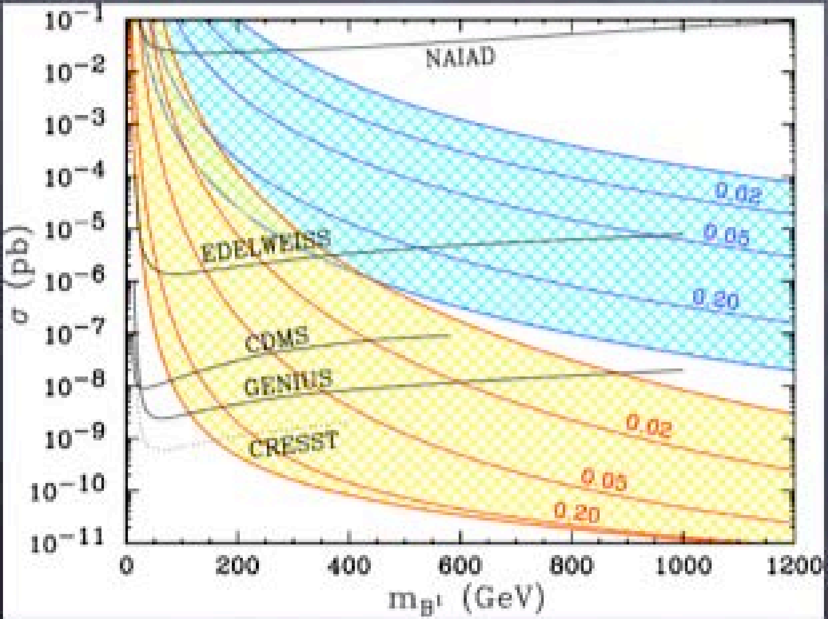
Experimental limits :

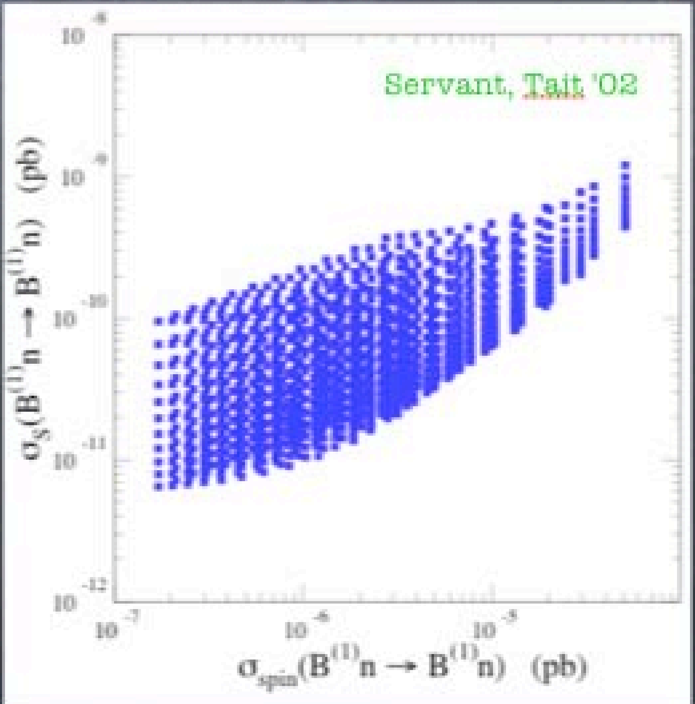


LKP signal :



Cheng, Feng, Matchev '02

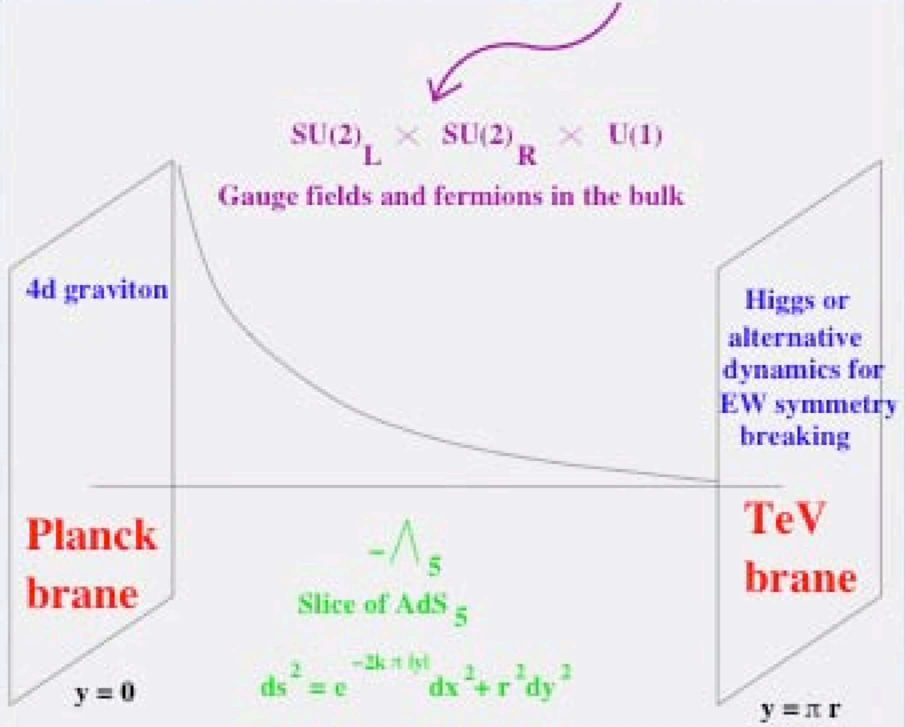




# Particle physics model building in warped space

2005 favourite set-up:

- ✔ hierarchy pb
- ✔ fermion masses
- ✔ High scale unification
- ✔ FRW cosmology

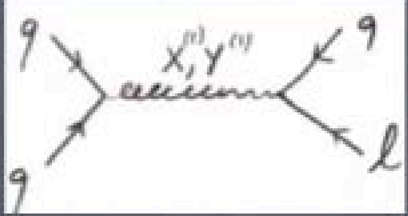


Now embed this into a GUT + solve proton stability

→

- ✔ Dark matter

In GUTs ⇒

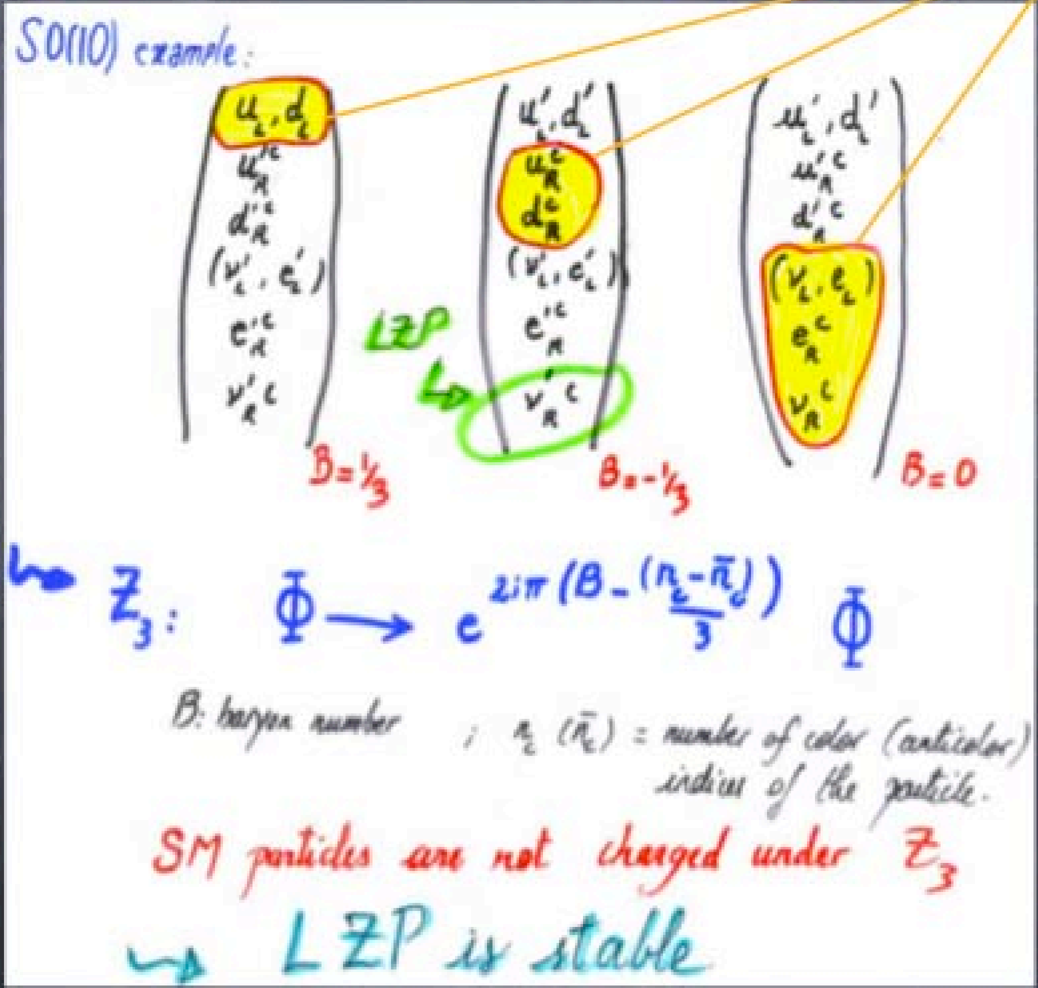


where $M_{X,Y}$ ~ few TeV

⇒ very fast proton decay

Solution: Break GUT by boundary conditions which split GUT multiplets

zero modes= SM fermions



SO(10) example:

$$\begin{pmatrix} u_L, d_L \\ u'^c_R \\ d'^c_R \\ (\nu'_L, e'_L) \\ e'^c_R \\ \nu'^c_R \end{pmatrix} \quad \begin{pmatrix} u'_L, d'_L \\ u^c_R \\ d^c_R \\ (\nu'_L, e'_L) \\ e'^c_R \\ \nu'^c_R \end{pmatrix} \quad \begin{pmatrix} u'_L, d'_L \\ u'^c_R \\ d'^c_R \\ (\nu_L, e_L) \\ e^c_R \\ \nu^c_R \end{pmatrix}$$

LZP ↳

$B = 1/3$ $\quad$ $B = -1/3$ $\quad$ $B = 0$

$$\hookrightarrow \mathbb{Z}_3 : \quad \Phi \longrightarrow e^{2i\pi \left(B - \frac{(n_c - \bar{n}_c)}{3}\right)} \Phi$$

B: baryon number ; $n_c$ ($\bar{n}_c$) = number of color (anticolor) indices of the particle.

SM particles are not charged under $\mathbb{Z}_3$

↳ LZP is stable

# Mass spectrum of KK fermions

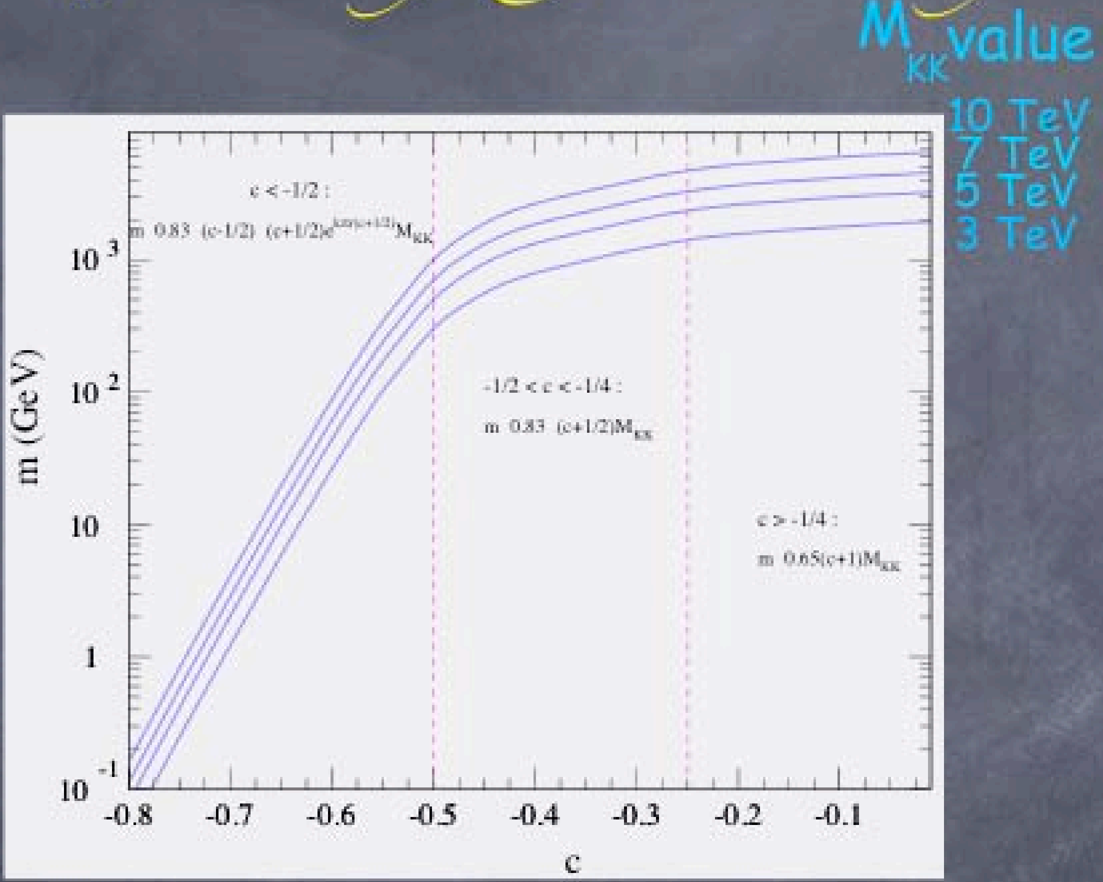
Depends on:

- ✔ type of boundary conditions on TeV and Planck branes
- ✔ c-parameter (=5D bulk mass)
  (=localization of zero-mode wave function)

For certain type of boundary conditions on fermions, there can be a hierarchy between the mass of KK fermion and the mass of KK gauge bosons

⇒ Not a single KK scale

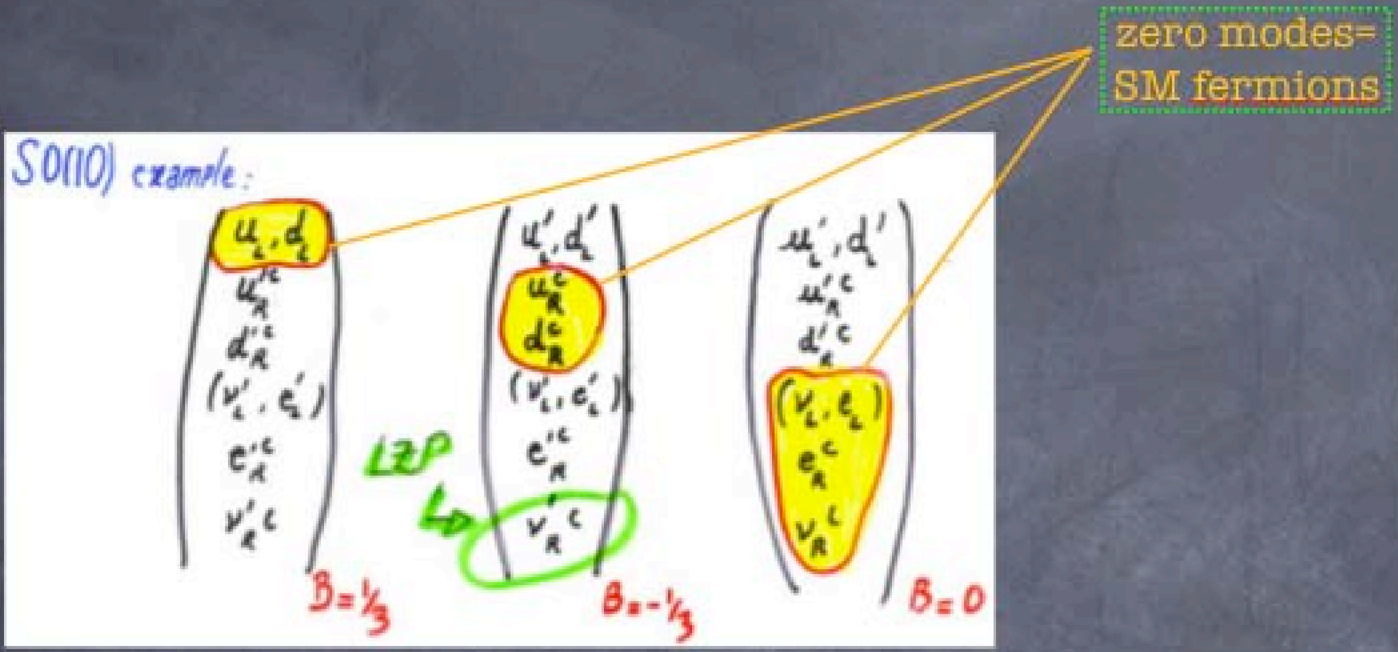
# *Mass spectrum of lightest KK fermion*



and smallest c: c of the top quark

⇒ LZP belongs to the multiplet containing SM top quark

There exists a very light KK fermion as a consequence of the heaviness of the top quark



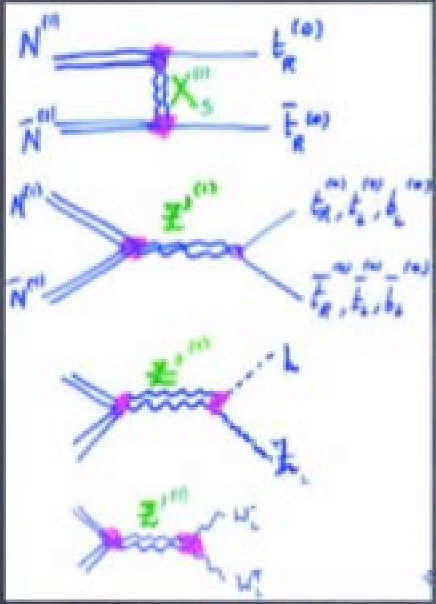
SO(10) example:

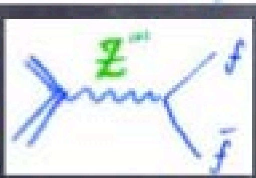
$$\begin{pmatrix} u_L, d_L \\ u'^c_R \\ d'^c_R \\ (\nu'_L, e'_L) \\ e'^c_R \\ \nu'^c_R \end{pmatrix} \quad B = 1/3 \qquad \begin{pmatrix} u'_L, d'_L \\ u^c_R \\ d^c_R \\ (\nu'_L, e'_L) \\ e'^c_R \\ \nu'^c_R \end{pmatrix} \quad B = -1/3 \qquad \begin{pmatrix} u'_L, d'_L \\ u'^c_R \\ d'^c_R \\ (\nu_L, e_L) \\ e^c_R \\ \nu^c_R \end{pmatrix} \quad B = 0$$

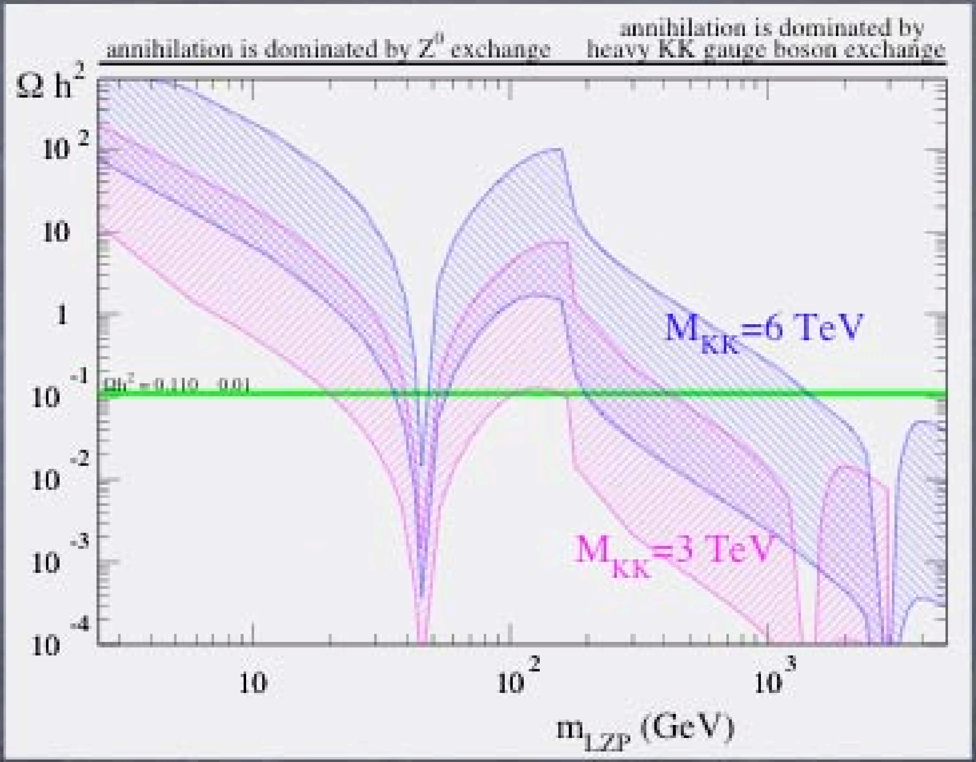
LZP

zero modes=
SM fermions

# Relic density predictions

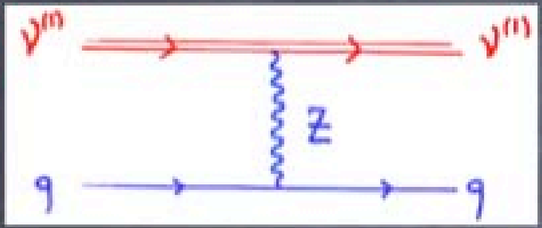






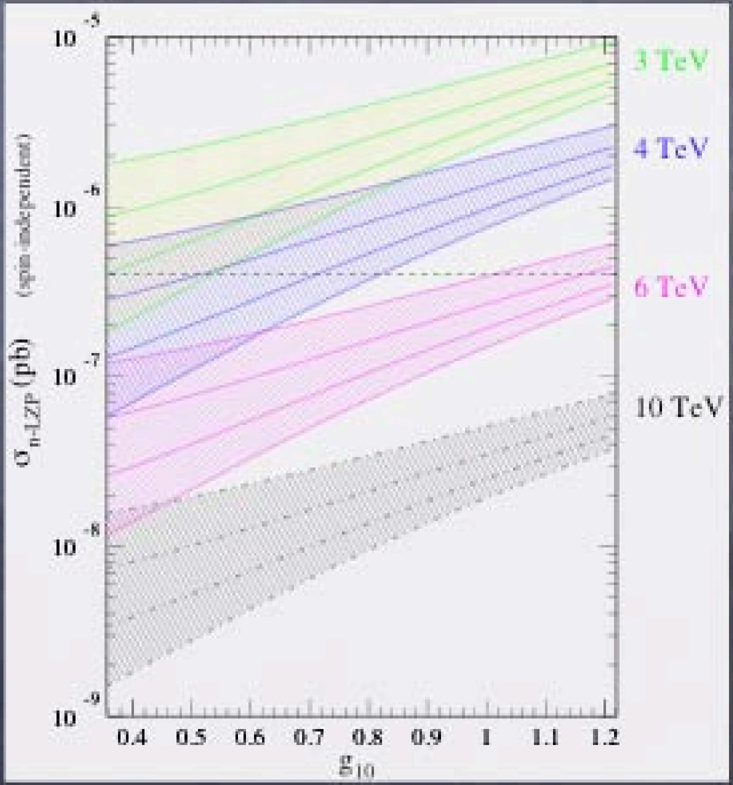
Agashe-Servant '04

# Direct detection



Wimp-nucleon elastic scattering cross section (spin-independent)

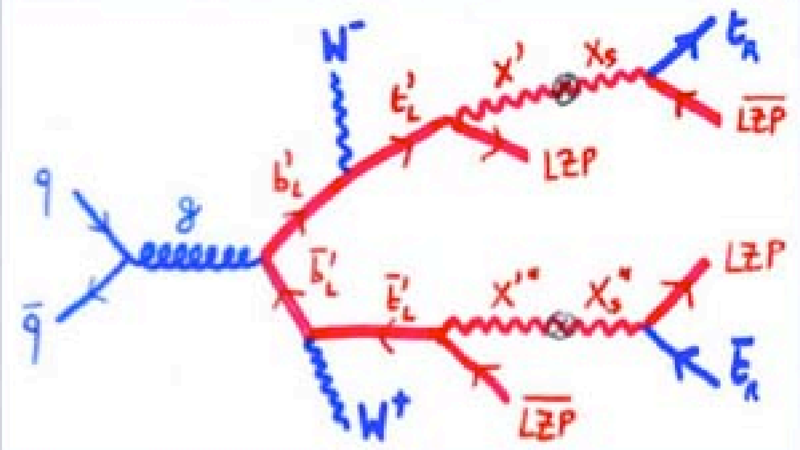
masses of KK gauge bosons



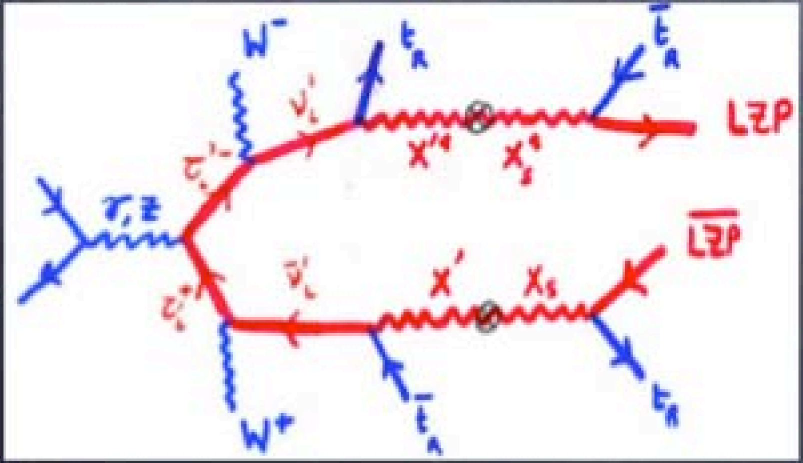
CDMS limit (only applies for some range of wimp masses)

Agashe-Servant '04

# Collider Signatures: examples



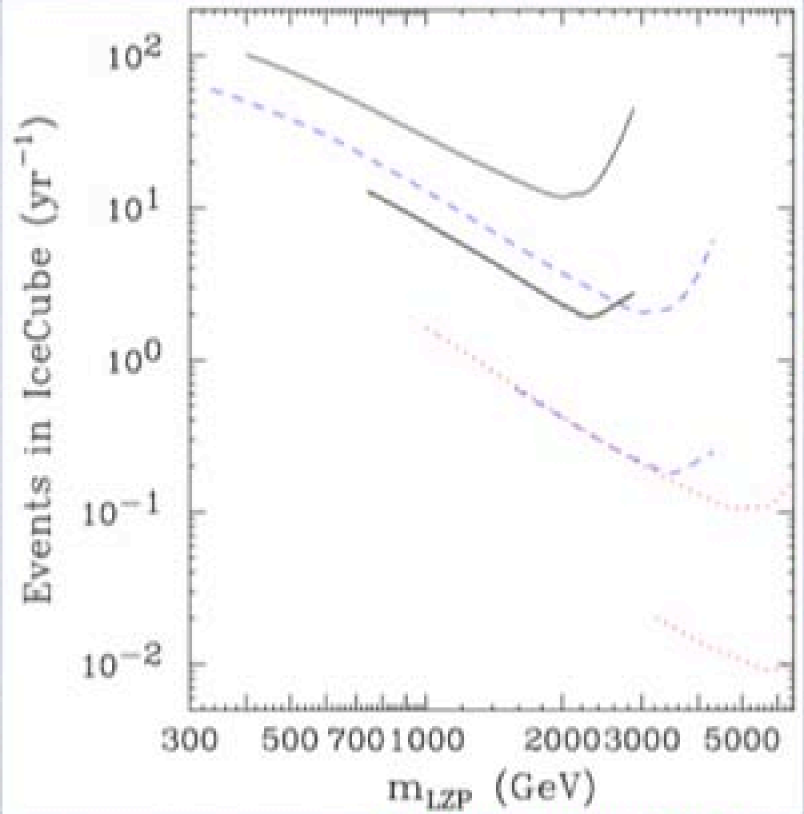
$\longrightarrow$ $4\,W + 2\,b + \not{E}_T$



$\longrightarrow$ $6\,W + 4\,b + \not{E}_T$

# Indirect detection in neutrino telescopes

Large elastic scattering cross section: large capture rate in the Sun
Efficient production of neutrinos in annihilations



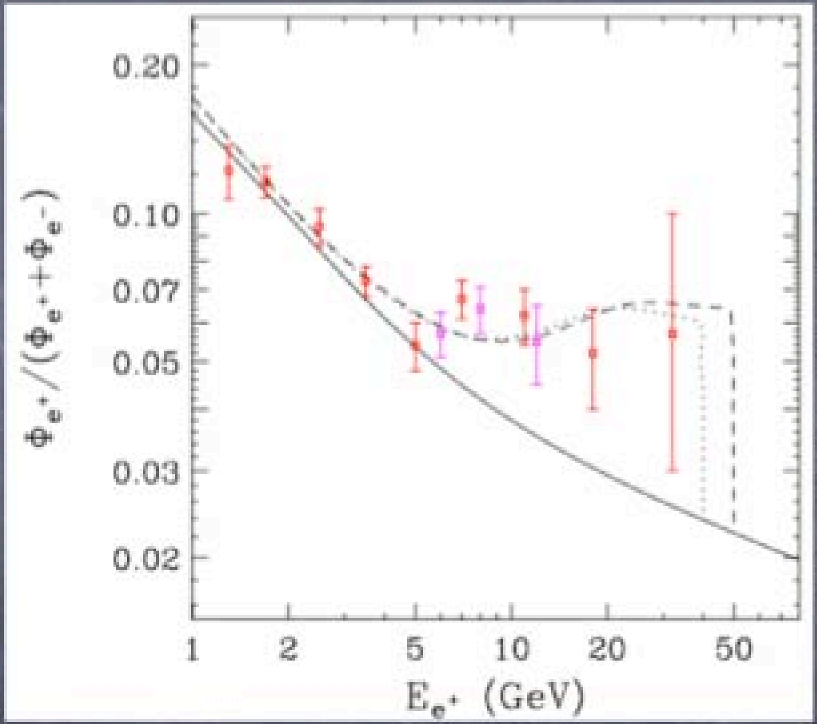
$M_{KK}$=4 TeV

$M_{KK}$=6 TeV

$M_{KK}$=10 TeV

Hooper & Servant '05

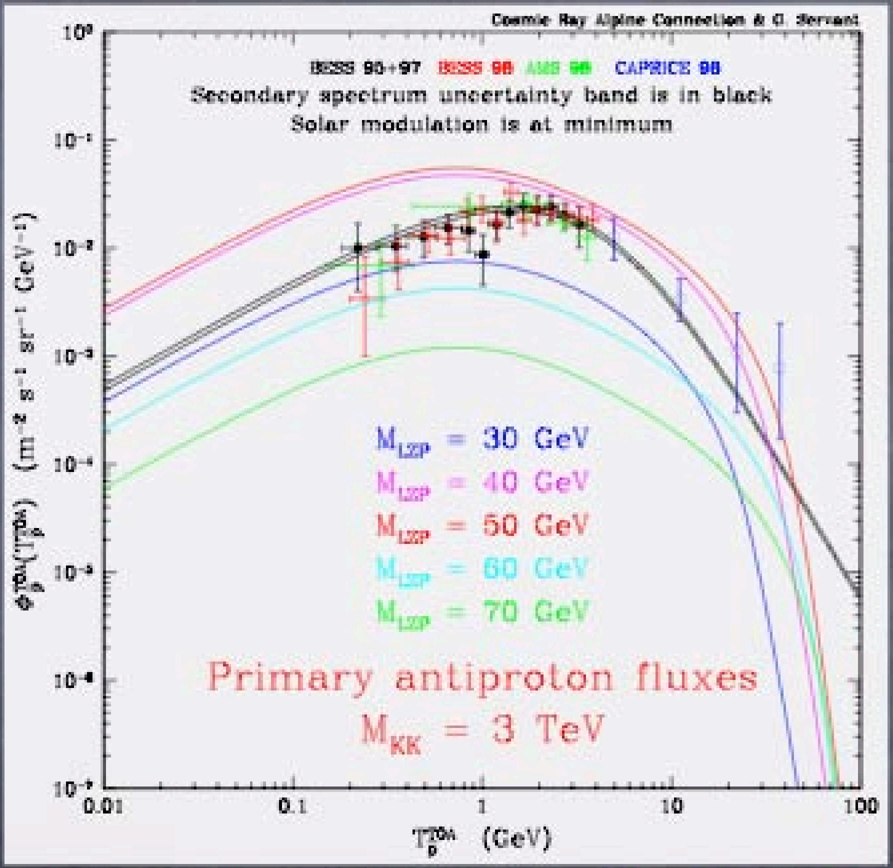
# Cosmic positrons from LZP annihilations



Hooper & Servant '05

Fit of the HEAT data from LZP annihilations

# Galactic antiprotons from LZP annihilation



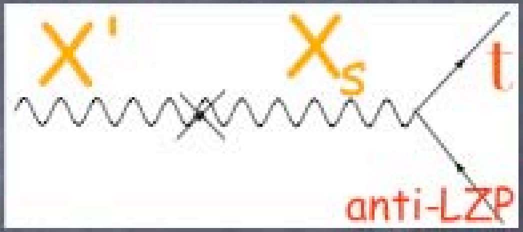
Barreau & al '05

# A natural framework to relate $\Omega_{\text{baryons}}$ and $\Omega_{\text{dark matter}}$

Our dark matter candidate carries baryon number! (B=1/3)

$$B_{\text{UNIVERSE}} = 0 = \underbrace{B}_{\text{carried by baryons}} + (\underbrace{-B}_{\text{carried by anti-LZP}})$$

Assume an asymmetry between t and $\bar{t}$ is created via the out-of-equilibrium and CP-violating decay :



Baryon number conservation leads to:

$$1/3\,(n_{\overline{LZP}} - n_{LZP}) = n_b - n_{\bar{b}}$$

Assuming efficient annihilation between LZP and $\overline{LZP}$ , and b and $\bar{b}$ :

$$\rho_{DM} = m_{LZP}\, n_{LZP} \approx 6\rho_b \longrightarrow m_{LZP} \approx 2\text{ GeV}$$

| | LKP | LZP | LSP |
|---|---|---|---|
| *nature* | gauge boson | Dirac fermion | Majorana fermion |
| *symmetry* | KK parity<br>$(-1)^n$ | $Z_3$<br>$B - \frac{(n_c - \bar{n}_c)}{3}$<br>related to proton stability | R-parity<br>$(-1)^{3(B-L)+2S}$ |
| *mass range* | ~600-1000 GeV | 20 GeV-few TeV | ~50 GeV-1 TeV |
| *annihilation cross section* | s-wave | s-wave | helicity suppressed (p-wave) |
| *favourite detection* | ✔ LHC<br>✔ Indirect detection | ✔ Direct detection!<br>✔ LHC!<br>✔ Indirect detection !<br>entire parameter space is testable | ✔ LHC |

# To conclude

Abundance of experimental activity related to dark matter detection:

- Colliders
- Direct detection: CDMS, Edelweiss, Dama, Cresst, Zeplin, Xenon, Naiad ...
- Indirect detection:
  - Gamma-ray telescopes: Hess, Veritas, Glast, Magic
  - Neutrino telescopes: Amanda, IceCube, Antares
  - Cosmic positron experiments: HEAT, Pamela, AMS-2

⇒It is timely to study the distinctive signatures expected in different dark matter scenarios.

LKPs, LZPs: viable alternatives to LSPs